Screened thermonuclear reactions and predictive stellar evolution of detached double-lined eclipsing binaries

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Abstract

The low energy fusion cross sections of charged-particle nuclear reactions (and the respective reaction rates) in stellar plasmas are enhanced due to plasma screening effects. We study the impact of those effects on predictive stellar evolution simulations for detached double-lined eclipsing binaries. We follow the evolution of binary systems (pre-main sequence or main sequence stars) with precisely determined radii and masses from $1.1\mathrm{M}_\odot$ to $23\mathrm{M}_\odot$ (from their birth until their present state). The results indicate that all the discrepancies between the screened and unscreened models (in terms of luminosity, stellar radius, and effective temperature) are within the observational uncertainties. Moreover, no nucleosynthetic or compositional variation was found due to screening corrections. Therefore all thermonuclear screening effects on the charged-particle nuclear reactions that occur in the binary stars considered in this work (from their birth until their present state) can be totally disregarded. In other words, all relevant charged-particle nuclear reactions can be safely assumed to take place in a vacuum, thus simplifying and accelerating the simulation processes.

PACS number(s): 24.10.-i, 25.10.+s, 26.20.+f, 97.80.

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The most effective tests of stellar evolution theory are provided by the sun and binary stars because their masses, radii, effective temperatures and luminosities can be determined with high accuracy [1,2].

Recently several papers appeared [3–5] which applied the *TYCHO* [6] stellar evolution code in an effort to assess its predictive capability by the critical evaluation of its assumptions. Ref. [3] presented baseline results from stellar models calculated using the *TYCHO* code, which were then tested against a subset of double-lined eclipsing binaries [7]. Other papers followed by the same group which elaborated on hydrodynamic regions [4] and/or included more realistic physics [5]. According to those studies the stellar evolutionary history of the sun (as well as of other stars) as predicted by solar evolution simulations is not unique. The main results are:

1) A model which fits the present day sun may be substantially inaccurate for other evolutionary stages and stars. The sources of this uncertainty are mainly the mixing length theory and the uncertainties in the solar abundances.

2) Diffusion has insufficient time to work on the pre-main sequence path (pre-MS) and does not affect the tracks

3) Hydrodynamic mixing (inertial-driven mixing) plays an important role in solar evolution only in the pre-MS path where there exists a small convective core (during partial CN burning).

Although Refs. [3–5] have studied in detail the effects of mixing and settling/diffusion on stellar predictive simulations, they have not investigated another source of uncertainty, which results from the fact that nuclear reactions in stellar interiors are influenced by the plasma which surrounds the reacting nuclei. Actually, neither version of the *TYCHO* code (6.0, 6.11) which are publicly available is equipped with screening corrections for the reaction rates, while the most recent application of *TYCHO* [5] despite its many improvements doesn't discuss this effect, either. It is obvious that thermonuclear screening might be the source of uncertainty to all efforts to simulate and predict the current state of double-lined eclipsing binaries, and that is why the present work is timely and relevant.

It should be emphasized that the effects of screening corrections on helioseismological aspects of stellar evolution is another major issue which has been studied extensively in Refs. [8–10] (and references therein). According to these papers the existence of screening effects in the solar interior can be proved by helioseismology [8] since the absence of such relevant corrections in computer simulations yields solar sound speed profiles which are incompatible with the seismic ones established by helioseismology (a discrepancy of the order of $\sim 1\%$ [8]).

Moreover, Ref. [10] proved that good agreement with the seismic sound profile is obtained from screening factors which do not deviate by more than $\pm 10\%$ from the standard screening prescription (i.e. Salpeter's formalism [11]). Therefore, since the screening model TYCHO has been recently equipped with (i.e. Mitler's one, see below) practically coincides [8] with Salpeter's one for solar conditions, all TYCHO solar evolution simulations (e.g. Ref. [5]) can now be more compatible with helioseismological and solar neutrino data.

The enhancing influence of stellar plasmas on astrophysical thermonuclear reactions (and on the respective thermonuclear reaction rates) has been studied by many authors (see for example Refs. [11–19], and references therein) who derive corrective factors (known

as Screening Enhancement Factors:SEFs) by which the reaction rates are multiplied in order to take into account screening effects.

We can define the SEF by using the usual definition [20] of the binary thermonuclear reaction rate r_{ij} per particle pair (i, j)

$$r_{ij} \sim \int_0^\infty S(E)\, P(E) \exp\left(-\frac{E}{kT}\right) dE \tag{1}$$

where the penetration factor $P(E)$ multiplied by the astrophysical factor $S(E)$ in the s-wave cross section formula

$$\sigma(E) = \frac{S(E)}{E} P(E) \tag{2}$$

is given by the WKB method:

$$P(E) = \exp\left[-\frac{2\sqrt{2\mu}}{\hbar} \int_R^{r_c(E)} \sqrt{V(r) - E}dr\right] \tag{3}$$

and the classical turning point (r_c) is the distance between the colliding nuclei at which the potential energy of the interaction $V_{SC}(r)$ equals their kinetic energy E so that:

$$V_{sc}(r_c) = E \tag{4}$$

The screening enhancement factor (f_{nr}) for non-resonant charged-particle reactions will be given by the ratio of the screened penetration factor $P_{SC}(E)$ with respect to the unscreened one $P_{NSC}(E)$ evaluated at the most effective energy of interaction E_0 so that:

$$f_{nr}(E_0) = P_{SC}(E_0) / P_{NSC}(E_0) \tag{5}$$

(For a detailed analysis of deriving SEFs see Ref. [17])

There is a variety of models, each of which has inherent limitations, while some of them have been the subject of intense controversy [21]. Some very widely used screening models are Salpeter's weak screening (WS) model (S) [11], Graboske-DeWitt's [22] and Mitler's one (M) [12]. Actually these models are frequently used in solar evolution codes giving quantitative estimates of the neutrino flux uncertainties associated with the screening effect(see for example Refs. [11–19] and references therein). Others studies [23] have dealt with strongly degenerate regimes where screening effects are extremely important. However, the effects of thermonuclear screening on the evolution of detached eclipsing binaries (focusing on the reaction rates and the relevant nucleosynthesis) has never been studied in detail.

TYCHO has been recently equipped by one of the authors (T.L.) with Mitler's [12] screening corrections for nuclear reaction rates which offers the opportunity to exhaustively investigate: a) the relevance of thermonuclear screening in stellar evolution and nucleosynthesis, and b) the error committed by not including such correction in relevant simulations [3–5].

The *TYCHO* code has been analyzed in detail in Refs [3,25] therefore we only briefly present the parameters of the version that we used. Actually, in all models created in the present paper we used the parameters adopted in Ref. [3] for consistency which will facilitate the study of the effects of thermonuclear screening. Namely, we used Timmes & Arnett's equation of state [3,26], opacities from Iglesias & Rogers (1996) [27] and Kurucz (1991) [28] for a solar abundance pattern from Anderse-Grevesse 1989 [29]. Although there are more recent solar abundances [30,31] which could also be used to produce compatible opacity tables we have decided to use the same mix [29] as that of Ref. [3,32] both in the construction of our initial models and the derivation of the OPAL Rosseland mean opacity tables. Following Ref. [3] we have selected the lower mass limit of our stars to be well above the limit of validity for our equation of state [3] $(1.1M_\odot < M)$.

In our simulations we apply the standard Schwartzchild convective theory [20] assuming that a mixing length (l) exists which is proportional to the pressure scale height (H_p) so that: $a_p = l/H_p$. Ref. [3] assumed that $a_p = 1.6$,while comparisons [33] between models with mixing lengths of $a_p = 1.5$ and $a_p = 1.9$ clearly support a value of $a_p = 1.9 \pm 0.1$. We have experimented using various mixing lengths in our simulations including of course the value of $a_p = 1.6$, so that we are compatible with Ref. [3]. No correlation was found between the mixing length and the screening enhancement factor in our models.

In this work we are interested in isolating the effects of thermonuclear screening, therefore we follow the methodology used in Ref. [3] avoiding optimization of all relevant parameters. Thus, we turn convective overshooting off while we also disregard all mass loss effects (the effects of the latter being minor anyway [3]). Rotational mixing was also turned off while the inertial-driven mixing (TYCHO v.6.11 [4]) was not taken into account.

In Ref. [3,5] a sample of stars $(1.1M_\odot < M < 23M_\odot)$ was used from Andersen's [7] double-lined eclipsing binaries which had precisely determined masses and radii. We used the same sample so that a direct comparison of the same code with and without thermonuclear screening corrections can be made.

The method followed in this work is plausible and simple: We follow the individual evolution of each member of the binary systems studied in Refs. [3,5] from their birth until their present state (using the ages indicated in Refs. [3,5]) with and without screening corrections for the nuclear reaction rates and we observe the differences between the two parallel tracks. Note that those ages have been obtained by following a plausible fitting procedure which fits the derived models to the observational data without using optimization for masses or abundances. Other methods (e.g. Ref. [34]) have adopted helium and heavy element variation but such a complex procedure would not serve any purpose in our study which aims at isolating the effect of screening rather than deriving the most accurate stellar evolution models.

The results indicate that all the discrepancies between the screened and unscreened models (in terms of luminosity, stellar radius and effective temperature) are within the current observational uncertainties. Moreover, no nucleosynthetic or compositional variation was found due to screening corrections. Therefore all thermonuclear screening effects on the charged-particle nuclear reactions that occur in the binary stars considered in this work (from their birth until their present state) can be totally disregarded. In other words, all relevant charged-particle nuclear reactions can be safely assumed to take place in a vacuum,

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Acknowledgments: This work was financially supported by *the Hellenic General Secretariat for Research and Technology (www.gsrt.gr)* under program *PENED 2003 (Space Sciences & Technologies)*.

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